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Preliminary Studies of the Use of Vertical-Cavity Surface-Emitting Semiconductor Lasers for Data Transmission in High Energy Physics Experiments[1]

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Abstract

Vertical-Cavity Surface-Emitting Laser Diodes (VCSEL's) have been irradiated at Fermilab with 8 GeV protons, up to a fluence of $(4.91 \pm 0.70)\times10^{13}$ protons/cm^2, with the aim of assessing their suitability for high speed data transmission from particle detectors used for High Energy Physics research. After irradiation, and two months of annealing at room temperature, there is a substantial decrease in the slope efficiency and an increase in threshold current, resulting in a power output that is about 67 % of its pre-irradiation level at a bias current 35 % above the pre-irradiation threshold. It has been estimated that the VCSEL's will have a useful life between two and three years, when exposed to the particle fluxes expected inside the tracking cavities of the collider experiments at Fermilab. Proximity coupling of the laser output to 62.5/125 μm (core/clad) multimode optical fibers was studied and found feasible. For a VCSEL to fiber distance of 0.5 mm, the coupling efficiency changes considerably with bias current, reaching a maximum of 67 %, while the alignment range is on the order of 140 μm. The alignment tolerance and coupling efficiency were little affected by the applied radiation dose.

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1. INTRODUCTION

With the constant development of cheaper and more complex electronic devices and solid state technologies, there is a trend towards the widespread use of finely segmented detectors for high resolution tracking and calorimetry in High Energy Physics experiments. As the channel density of new particle detectors increases, the problem of bringing the data out of them, while minimizing the mass and size of the dataways, becomes daunting. For example, the upgrade of the D∅ Experiment at Fermilab will include a large silicon tracker [1], with approximately 800 000 channels taking data from proton-antiproton collisions occurring every 132 ns. At the front end, the signals from the tracker will be digitized by custom-designed integrated circuits (SVX-II [2]), located very close to the detectors, and transferred to the subsequent data processing and acquisition systems located approximately 28 ft away. In the current design, this transmission will use approximately 14000 metallic data paths, based on custom-designed strip cables and high bandwidth miniature multi-coaxial cables, at a rate of 53 Mwords/s in parallel [3]. The main concern on using metallic paths is their size and mass, given the fact that the cables should traverse the whole central tracking region in order to come out through the edges of the central calorimeter.

Because the overriding design consideration for the transmission system is its mass, a metallic connection may not be the best alternative. Hence, the advantages of optical over electrical transmission are being studied. Using a serial optical link running at 1 Gbit/s, approximately 14000 wires could be replaced by 588 optical fibers, in the silicon tracker alone, reducing considerably the cabling problem. Additionally, because all the front-end electronics are mounted very close to the silicon detectors, very little electrical power and space are available for the data transceivers. Power dissipation should be kept to a minimum to avoid heating the silicon detectors. For these reasons Vertical-Cavity Surface-Emitting Laser Diodes (VCSEL's) [4, 5] seem well suited for this application; they exhibit low operating currents, high modulation bandwidth and small size. The bare dies can be mounted next to the digitizing electronics (also in die form) and, due to their vertical structure, are easily coupled to optical fibers by simple proximity focusing [6, 7, 8].

Since the VCSEL's would be located inside the silicon tracker, their tolerance to radiation becomes a concern. With the Tevatron delivering an integrated luminosity of 2000 pb^{-1}/year to the interaction region during Run II, the VCSEL's located closest to the beam (2.78 cm radial distance) would be exposed to approximately 3.1×10^{13} charged hadrons, mainly pions, and 3.6×10^{12} neutrons per cm^2 per year [9]. In order to understand their behavior under irradiation, one VCSEL was irradiated with 8 GeV protons at the Fermilab Irradiation Facility. Some of its parameters were measured before and after the exposure, and it was also compared to non-irradiated VCSEL's.

The device chosen was manufactured by Vixel Corp. (Colorado, USA) using AlGaAs, under series number LA-M-850 [10]. It has a typical peak wavelength of 850 nm and can deliver up to 3 mW of optical power. According to the data-sheet, the threshold current and slope efficiency are typically 7 mA and 0.7 mW/mA, respectively; but for all the devices the measured threshold was very close to 9.6 mA. The manufacturer claims that it can handle data rates up to 5 Gbits/s but this has not yet been verified.

2. IRRADIATION PROCEDURE

This irradiation was performed at the Fermilab Irradiation Facility, located in one of the Booster's beam dump lines. This line provided a pulsed beam of 8 GeV protons with intensities between 7×10^{8} and 1.5×10^{9} protons per pulse with a period of 2.9 s to 6 s, resulting in an average flux between 1.3×10^{7} and 2.6×10^{8} protons/s·cm^2. The dose was measured on-line with a beam current monitor, and off-line by analysis of the activation of Al foils placed in front of the VCSEL. The total dose delivered to the device was $(4.91 \pm 0.70)\times10^{13}$ protons/cm^2, with the protons traversing the laser diode in a path perpendicular to the cavity (perpendicular to current flow and light output).

During the exposure, the VCSEL was located in a gas- and light-tight box, whose ambient temperature was controlled to 5°C ± 1°C. Dry nitrogen was circulated through the box to keep the humidity as low as possible and avoid condensation over the devices. Cooling was necessary to dissipate the energy deposited by the beam on the devices, and because some devices for another experiment, that had to be kept at 5°C, were irradiated at the same time. This box was mounted on an X-Y motorized table that enabled us to sweep the samples across the beam. The VCSEL was biased at a current 35 % above the pre-irradiation threshold (13 mA, continuous) and the light was transmitted to a photodiode by means of a silica-core multimode optical fiber, 62.5/125 μm (core/clad) in diameter, coupled to the VCSEL by proximity. The distance from the VCSEL to the fiber was approximately 1 mm, resulting in a coupling efficiency of about 35 %.

3. RESULTS

3.1. Output Power and Threshold

Figure 1 shows the change in the optical power delivered by the VCSEL (relative to the initial power) as a function of proton fluence. The decrease in output power seems to be fairly linear and a straight line was fitted to the data, giving a slope of $(-1.20 \pm 0.18)\times10^{-14}$ cm^2. The uncertainty in the optical power, at the points shown in the plot, was primarily introduced by changes on the order of ±0.3°C in the temperature of the irradiation chamber that were correlated with changes in the light output. The exact temperature of the device is not known because only the ambient of the chamber was monitored. Without accurate information about the temperature changes of the VCSEL itself, it was not possible to correct for the changes in light output induced by them. At the end of the irradiation the optical fiber used to transmit the light to the photodiode exhibited very strong attenuation at visible wavelengths, and a 6 %

transmission loss at the VCSEL wavelength (850 nm)[2]. The data points in Figure 1 were corrected for the radiation-induced loss in the fiber, according to a power-law model of the damage as a function of fluence [11, 12]. Figure 2 shows the optical power as a function of bias current, for a non-irradiated VCSEL and the irradiated one, 64 days after the end of the exposure. During those 64 days the VCSEL was stored *unbiased* at room temperature, resulting in significant annealing of the damage. At the end of the irradiation the light output at 13 mA had decreased to around 46 % of the initial level, recovering to 67 % after 64 days, with no further annealing being observed. Thirty hours after the end of the exposure, with the device still in the chamber refrigerated at 5°C and biased, the output power had recovered to around 54 % of the initial level. Unfortunately, many of the characteristics of the exposed device were not appropriately measured before irradiation so non-irradiated VCSEL's had to be used for comparison. This decision was supported by the fact that three non-irradiated devices, from the same batch as the irradiated one, exhibit essentially the same behavior. All measurements after the exposure were performed at room temperature.

As Figure 2 shows, the threshold current increased from 9.6 mA to 10.1 mA (5.2 %) after irradiation, and the slope efficiency above threshold decreased by 14.3 %. There is no significant change in the forward voltage-current characteristic after exposure. According to Ref. [13], the main effect of *neutron* radiation observed on edge-emitting laser diodes is the introduction of non-radiative recombination centers, causing a decrease in the amount of carriers available for stimulated emission, thus increasing the threshold but affecting the slope efficiency very little. The reason given for this [13] is that since the internal quantum efficiency well above threshold is dominated by the very short stimulated radiative recombination lifetime, a very large density of non-radiative recombination centers is necessary to make the non-radiative lifetime small enough to affect the slope efficiency. The increased recombination will simply act like a drain that diverts a fixed amount of the injected current away from the lasing action, effectively increasing the threshold but not changing the slope above it. Moreover, the introduction of recombination centers would increase the current at low forward voltages, which is not the case in our irradiated VCSEL. The fact that we observe a significant change in slope and no increase in current may point to a different damage mechanism for protons. H. T. Minden [14] proposed that proton bombardment creates hole trap levels in the active region which, along with decreasing the amount of carriers available for radiative recombination, can lead to transitions that increase the optical absorption at the lasing wavelength, thus lowering the gain of the cavity. Photoluminescence of proton-irradiated GaAs also suggest a reduction of carriers available for light emission as a result of trapping [15]. Unfortunately, at this point we do not have the means to verify this experimentally.

Looking towards the use of VCSEL's inside particle detectors, it is important to be able to predict the lifetime of the devices when exposed to the particle fluences expected during the next collider run of the Tevatron at Fermilab. Assuming that our irradiated VCSEL has annealed completely and that the final damage (after annealing) increases linearly with fluence, we could estimate the fluence necessary to reach a certain lower limit of allowable intensity for a given driving current. Since the irradiation rate is much lower in the collision hall than during the tests, the annealing

[2] This fiber had been used in a previous irradiation, where it was exposed to a fluence of $(1.8 \pm 0.2)\times10^{13}$ protons/cm^2 with no

would be completed while the irradiation occurs, as long as the temperature of the device is high enough. At D∅ the whole silicon tracker will be kept at around 0°C but the VCSEL cavity would be at a higher temperature when it is operated (at least 10°C, assuming a thermal resistance of 450 K/W [5]), resulting in significant annealing. In this case, the optical power had decreased to 67 % of the initial value after a fluence of 4.91×10^{13} protons/cm^2 and annealing, resulting in a damage rate of 6.7×10^{-15} cm^2 (at a peak current of 13 mA, 35 % above the initial threshold). Given this damage rate, the intensity will reach zero after a fluence of approximately 1.5×10^{14} protons/cm^2, which is equivalent to four years of operation of the Tevatron at the nominal luminosity expected during Run II. Considering that the predicted life of the inner layer of silicon detectors is approximately three years [16], the VCSEL's will remain operational longer than the detector. In the worst case, assuming minimum annealing and using the damage rate shown in Figure 1 (1.20×10^{-14} cm^2), the expected life of the VCSEL's is between two and three years (taking into account the uncertainties). Obviously, the life of the devices can be extended beyond these limits if the driving current is increased. It is also very important to keep in mind that these estimates are very approximate, largely because the predicted particle flux in the central regions of the detector has large uncertainties and it is mostly composed of pions, whose effects on semiconductors are significantly different, in kind and magnitude, from those of protons [15, 17, 18]. In *silicon* pions produce between 25 % and 80% less displacement damage than protons, in the energy range between 1 MeV and 10 GeV, with the difference being larger for lower energies [18]. We do not have knowledge of any study of the damage produced by *pions* on GaAs in general, or laser diodes in particular.

3.2. Optical Fiber Coupling

One of the advantages of using VCSEL's is the possibility of directly coupling the fiber by proximity to the bare laser die [6, 7, 8], but this coupling has to be extremely reliable and simple to be useful in a big particle detector. The failure of only one of the hundreds of VCSEL's in the detector (or even thousands, in future detectors) would render a large section of it completely useless. Space is very limited, as we said earlier, so the coupling has to be made with a minimum of hardware; and there is no way to replace or repair any damaged devices once the detector is installed, aligned, and sealed inside the collision hall, where it will remain for many years. The tracking region will be virtually impossible to access; first, because the alignment of the detectors is extremely delicate (tolerance is on the order of ±10 μm in the direction perpendicular to the beam [1]), and second, because it is sealed to maintain a carefully controlled atmosphere (dry and cold).

The coupling efficiency and transverse alignment tolerance were measured for both a non-irradiated and an irradiated VCSEL. They were also expected to change with current because of the multiple transverse modes in which the device can lase, and the broadening of the beam as the current increases. In fact, the far-field pattern of the irradiated VCSEL becomes "donut"-shaped for bias currents close to 14 mA, indicating the onset of higher transverse

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measurable damage.

modes of oscillation that limit the coupling efficiency. For these tests, a 62.5/125 μm (core/clad) multimode silica-core fiber was placed in front of the VCSEL, at (0.5 ± 0.05) mm from its surface, without using any light-guiding material between them. The fiber was positioned transversally by searching the maximum coupled power with the laser biased at 13 mA. Figure 3 shows the coupling efficiency as a function of bias current. It is clear from the figure that for large currents, with the appearance of secondary transverse modes and the broadening of the beam, the coupled power drops substantially even though the overall power delivered by the laser is increasing. A drop of about 5% in the maximum coupling efficiency is observed after irradiation, probably caused by changes in the transverse structure of the beam. Additionally, the shift in threshold current causes an increase in efficiency for currents above 11.75 mA.

Figure 4 shows the variation in power coupled to the fiber as it is displaced transversally from the point of maximum efficiency, for the irradiated and non-irradiated VCSEL's. Gaussians with the standard deviations shown in Table 1 were fitted to the points, indicating a slight narrowing of the beam after irradiation. Standard optical receivers can deliver Bit Error Rates (BER) on the order of 10^{-12} or less when receiving at least 20 μW, so the fiber can be displaced transversally as much as 69 μm from the optimal point (after irradiation, at 13 mA peak current) with the fiber located 0.5 mm from the VCSEL, without compromising the quality of the transmitted data. For improved tolerance the fiber can be located farther from the VCSEL, at the expense of lower peak intensity. For example, at 1.5 mm the displacement from the optimal point can be 94 μm, resulting in a coupled power on the order of 20 μW (after irradiation, at 13 mA peak current).

Device \ Bias	11 mA	12 mA	13 mA	13mA, ΔZ = 1.5 mm
Non-irradiated	25 μm	27 μm	31 μm	64 μm
Irradiated	-	26 μm	29 μm	55 μm

Table 1: Transverse fiber alignment tolerance expressed as the standard deviation of the gaussians fitted to the data shown in Figure 4. The column labeled "13 mA, ΔZ = 1.5 mm" corresponds to a fiber-VCSEL distance of 1.5 mm.

4. CONCLUSIONS

It has been shown that Vertical-Cavity Surface-Emitting Laser Diodes (VCSEL's) could be used for data transmission from High Energy Physics detectors, where tolerance to radiation, small size, and reliability are essential.

After irradiation with 8GeV protons, up to a fluence of 4.9×10^{13} protons/cm^2, and 64 days of annealing at room temperature, the threshold had increased by 5 %, while the slope efficiency decreased by 14 %, resulting in a 33 % drop in light power output for a driving current 35 % above the pre-irradiation threshold. The behavior of the exposed VCSEL suggests a damage mechanism, resulting from proton irradiation, different from that reported in the literature after neutron bombardment of conventional edge-emitting laser diodes. The worst case damage rate, assuming minimum annealing and a fixed driving current, gives an estimate of the useful life of the devices between two and three years; which can be extended by allowing for a higher driving current. This is comparable to the predicted life of the inner layers of the silicon tracker being built at Fermilab for the D∅ Upgrade.

The possibility of easy coupling of the VCSEL to a 62.5/125 μm (core/clad) multimode optical fiber by proximity focusing has been studied with encouraging results. The range in the transverse position of the fiber is approximately 138 μm for a VCSEL to fiber distance of 0.5 mm, allowing for a minimum coupled power on the order of 20 μW. The maximum coupling efficiency, for a VCSEL to fiber distance of 0.5 mm, is higher than 65 % but changes considerably with the laser bias current. Irradiation, up to the fluence indicated above, does not substantially affect the fiber positioning tolerance or the coupling efficiency. Obviously, the use of large-core fibers will make the efficiency higher and the alignment easier, but we think that it is perfectly feasible to use conventional 62.5 μm core fibers.

5. ACKNOWLEDGMENTS

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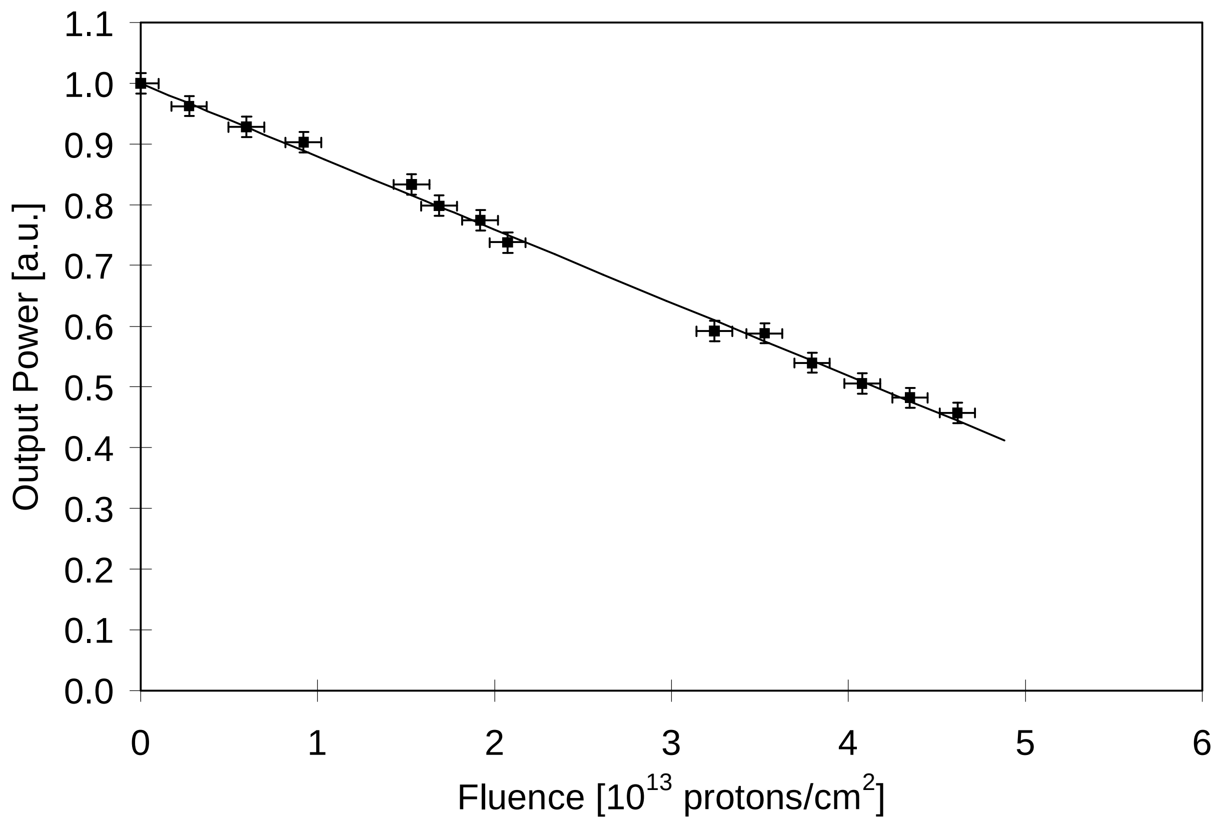


Figure 1: Change in the optical power delivered by the VCSEL during exposure to 8 GeV protons, as a function of the fluence, for constant bias current. A straight line was fitted to the data, giving a slope of (-1.20 $\pm$ 0.18)$\times 10^{-14}$ cm^2.

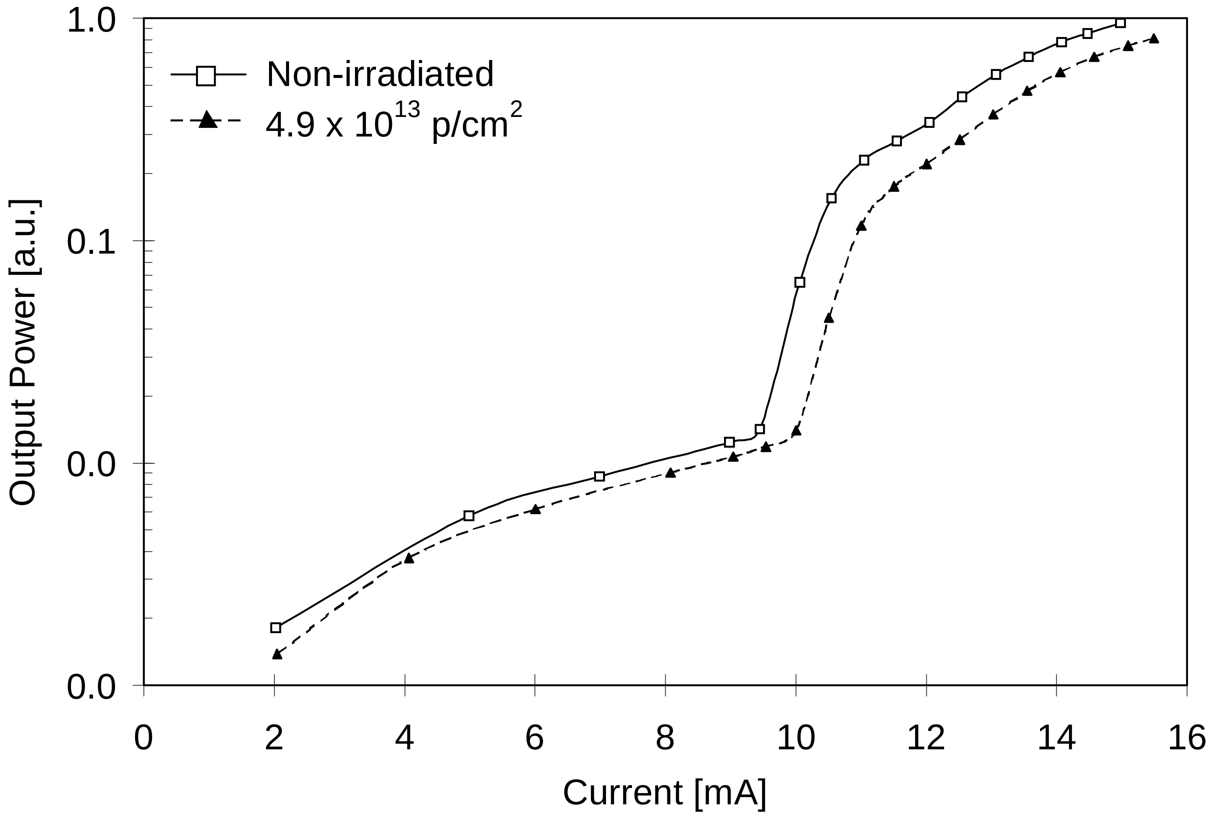


Figure 2: Optical power output as a function of bias current, for a non-irradiated VCSEL, and for the irradiated one 64 days after the end of the exposure.

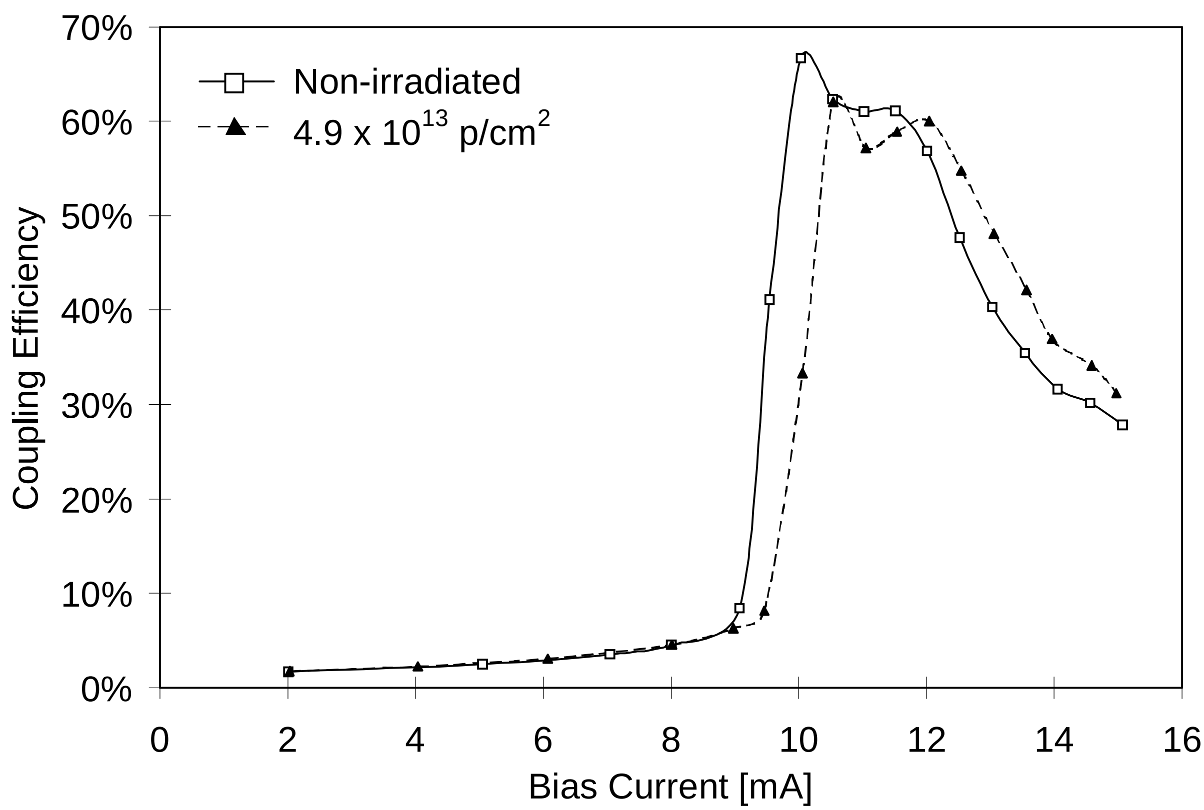
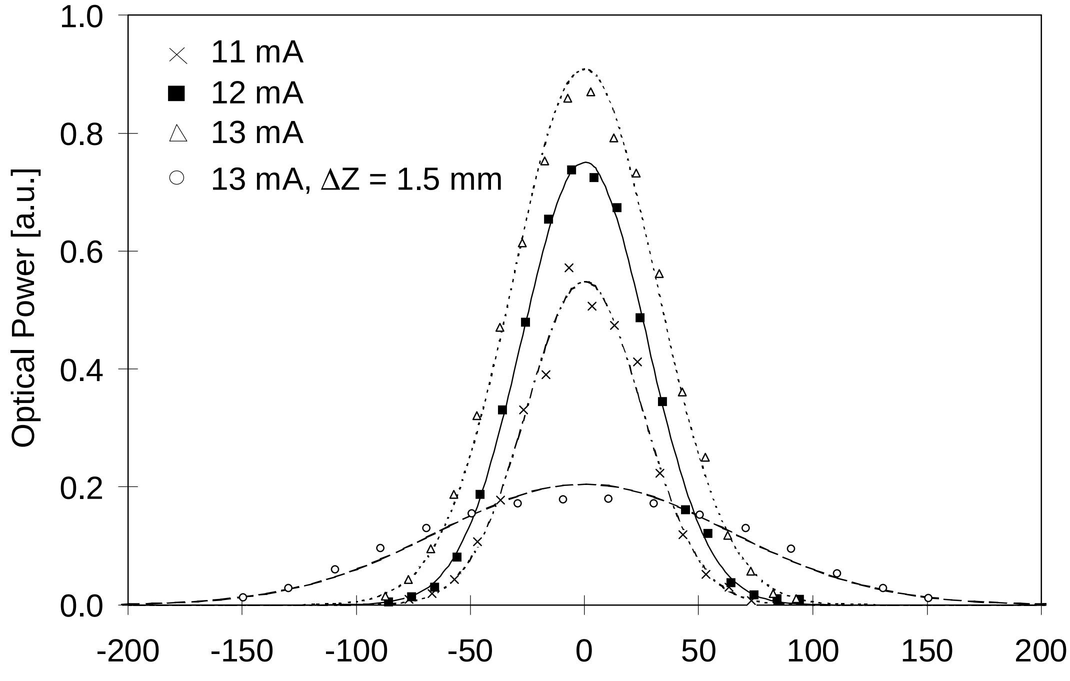


Figure 3: Power coupling efficiency to a 62.5/125 μm optical fiber, as a function of VCSEL bias current. The distance between the fiber and the VCSEL was (0.5 ± 0.05) mm.



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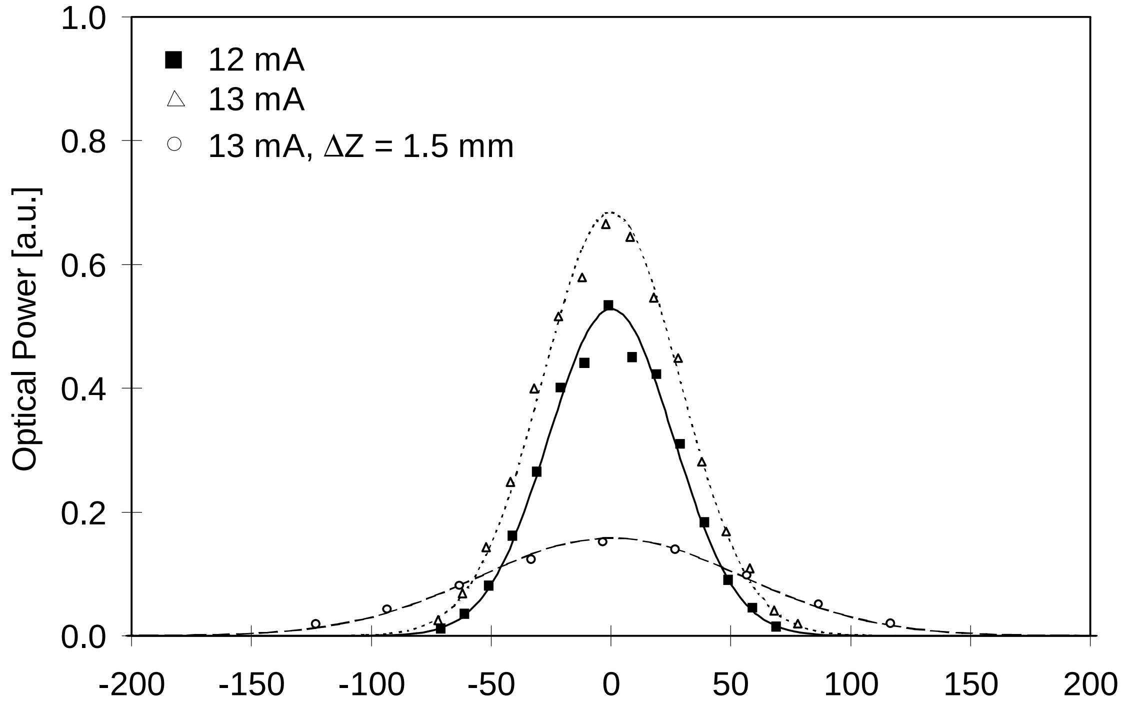

b.

Figure 4: VCSEL power coupled to a 62.5/125 μm fiber (located 0.5 ± 0.05 mm from the VCSEL), as a function of transverse fiber displacement, for different bias currents: (a) non-irradiated, (b) irradiated. The points indicate the actual measurements and the curves are gaussian fits to those points (see Table 1). The points labeled as “13mA, ΔZ=1.5mm” correspond to a fiber-VCSEL distance of 1.5 mm.